BEHAVIOR OF REINFORCED STONE COLUMN

A thesis submitted in partial fulfillment of the requirements for the award of the dual degree of

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By

PAWAN KUMAR CHAMLING
(Roll No.-710ce1002)

Under the Supervision of

Prof S. P. Singh

DEPARTMENT OF CIVIL ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY
ROURKELA-769008, INDIA
2015

DEPARTMENT OF CIVIL ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY ROURKELA
ROURKELA-769008, ORISSA, INDIA

CERTIFICATE

This to certify that the thesis entitled ***"Effects of Strength of Confining Material And Loading Area on Stone Column"*** submitted by **Pawan Kumar Chamling** in the partial fulfilment of the requirements for the award of Bachelor of Technology and Master of Technology Dual Degree in **Civil Engineering** with specialization in **Geotechnical Engineering** during session 2014-15 at the National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in this report has not been submitted to any other university/institute for the award of any degree or diploma.

Date:
Place: Rourkela

Prof. S. P. Singh
Department of Civil Engineering

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Pawan Kumar Chamling

(710ce1002)

ABSTRACT

Rapid industrialization and large scale infrastructure development results in depletion of normal useful land and it simultaneously promotes the use of marginal and weak soil for infrastructure development. Some problematical soils like soft clay deposits, marine clays, recent fills, peat soils, etc. pose problems in construction because of very low bearing capacity, high compressibility and trend for lateral flow etc. These types of grounds need treatment to improve their engineering behavior as per design requirements of structure. One common technique for treating these soils is installation of stone columns. Stone columns derives its load carrying capacity from the confinement offered by the surrounding soil. Encasement of stone column has been extended the utilization of stone columns to soft clays.

In present study, we provide two types of extra confinement externally and internally and these are circumferential encasement, circular horizontal strips and combination of two. An axisymmetric analysis was carried out using Mohr-Coulomb's criterion considering elasto-plastic behaviour for soft clay and stone.

Three type of surrounding is considered 7, 14, 30 kPa and the load carrying capacity of footings located over stone columns is compared with equal size of footings located on the virgin soil that is without a stone column underneath. Result shows that as strength of surrounding soil increases effect of extra confinement decreases. For low strength of surrounding soil full length of encasement is more effective but for high strength of surrounding soil partial length of encasement is sufficient.

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CHAPTER 1

INTRODUCTION

1.1. INTRODUCTION

Due to the rapid industrialization and large scale infrastructure development, there is going to be lack of useful land. In general practice, the construction is done only on normal useful land. The otherwise useless grounds like municipal solid waste dump sites, sites with marine clays, compressible soils or reclaimed lands etc. are now worthy of construction purpose. Construction on these type of land is a challenge so ground improvement technique are preferred due to economical consideration. It has been always challenging task to provide safe and sound foundations for structure with high loads and permissible low settlements. The general practice is to improve the capacity of ground by various means, e.g., pre-compression, vibration, compaction grouting, dynamic compaction, explosion, woven fabric reinforcement etc. Now a days, stone columns (granular piles) are successfully used to improve the desire properties of the soft clay due to its effectiveness and ease of installation.

1.2 STONE COLUMN

Stone column consists of granular material compacted in long cylindrical hole. Main aim of inserting a stone column is to replace a percentage of the soft clay with stiffer granular material so that it could tolerate the load of the structure. These stone columns or granular piles are more economical where gravel, crushed rock and sand are available in abundance nearby. Greater stiffness of stone column compared to that of the surrounding soil reasons a large portion of load to be transferred to the columns. The entire soil below the foundation, therefore act as a reinforced soil with higher load carrying capacity than the virgin soil. Stone column derives its load carrying capacity from the confinement offered by the surrounding soil.

1.2.1 Advantage of Stone Column

Stone columns are extensively used to

- Improve the bearing capacity of poor ground to make it possible to use shallow foundation on the soil.
- Increase time rate of settlements, stiffness.
- Enhance shearing strength of soil, drainage condition and environmental control.
- Reduce the settlement of structure.
- Reduce liquefaction potential of soft ground.

1.2.2 Construction Methodology of Stone Column

The use of stone columns or granular piles as a ground improvement technique is generally adopted in clayey or silty-clayey soils. If the granular material or crushed stone is filled in boreholes and compacted properly, the resulting structure is called stone column. Stone columns reinforcement can be by using either replacement or displacement methods. So, stone columns can be constructed by the following two methods:

1) Ramming method
2) Vibro-replacement method
    a) Wet top feed method
    b) Dry bottom feed method

1) Ramming Method

This method of installation of stone column is proposed by Datye and Nagaraju (1985). In this method, a pre-bored hole is filled with granular material and compacted by a heavyweight rammer over the borehole. The bore hole is made by bailer with casing to full length. The casing maintains the stability of borehole. The stone columns are essential to function as drainage and it is instructed not to use bentonite slurry for preserving the stability of the borehole. This method has advanced in India and it is gaining significance. A cased hole of essential size is bored using flap valve bailer with casing tube of necessary size. After the casing tube is driven to required depth, the hole is filled with granular material. Casing tube is and granular fill compacted by heavyweight rammer. The filling of the granular material, withdrawal of the casing tube and ramming of fill should be so skillful as to have continuous column of stone. Compaction was achieved by a heavyweight rammer generally of 1.5 to 2 tonnes and falling over a height of 1 to 2 m.

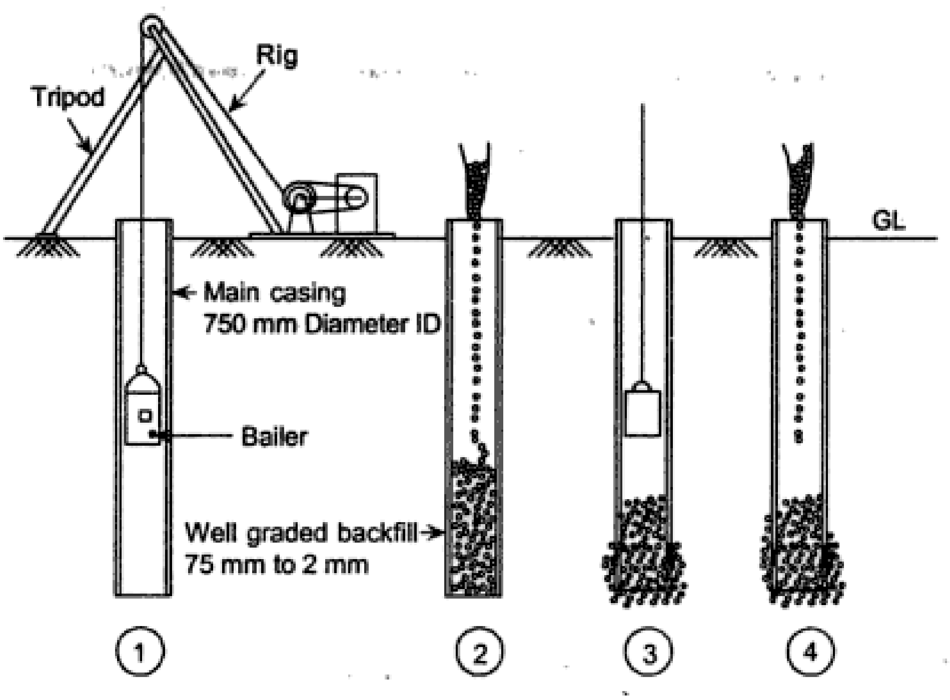

Fig. 1.1 Stone column installed by ramming method (Datye and Nagaraju 1975)

2) Vibro-replacement method

In this method, the stone columns are constructed using a vibrofloat. The vibroflot sinks in the ground under its own weight with the assistance of water jet and vibrator. A typical vibrator would be 3 to 5 m long with a mass of 2-8 tonnes. Vibro-replacement stone columns are assembled by either the wet top feed method or by the dry bottom feed method.

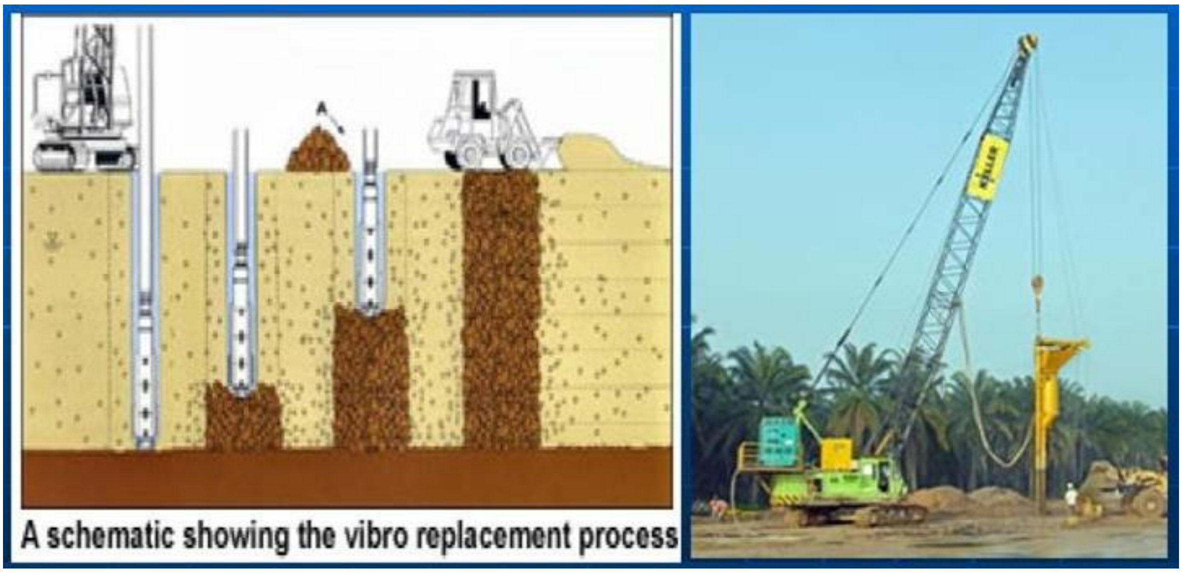

Fig. 1.2 Vibro-replacement method

a) Wet top feed method

In the wet top feed method, the bottom water jet is opened which is resulting in a saturated mass of soil ready to penetration and compaction by vibrator. The stone chips(crushed stone or recycled concrete) is then added at the ground surface around the vibrator which creates the stone column.

Fig. 1.3 Wet top feed method

b) Dry bottom feed method

The dry bottom feed method is similar as wet top feed method except that no water jet is used and the stone chips are fed through vibrator tip with a feed pipe attached to the vibrator. Pre boring of dense strata at the location of column may be required for the vibrator to penetrate the required design depth. During the process of withdrawal of vibrator, vibration is continuously maintained to ensure necessary compaction of granular material.

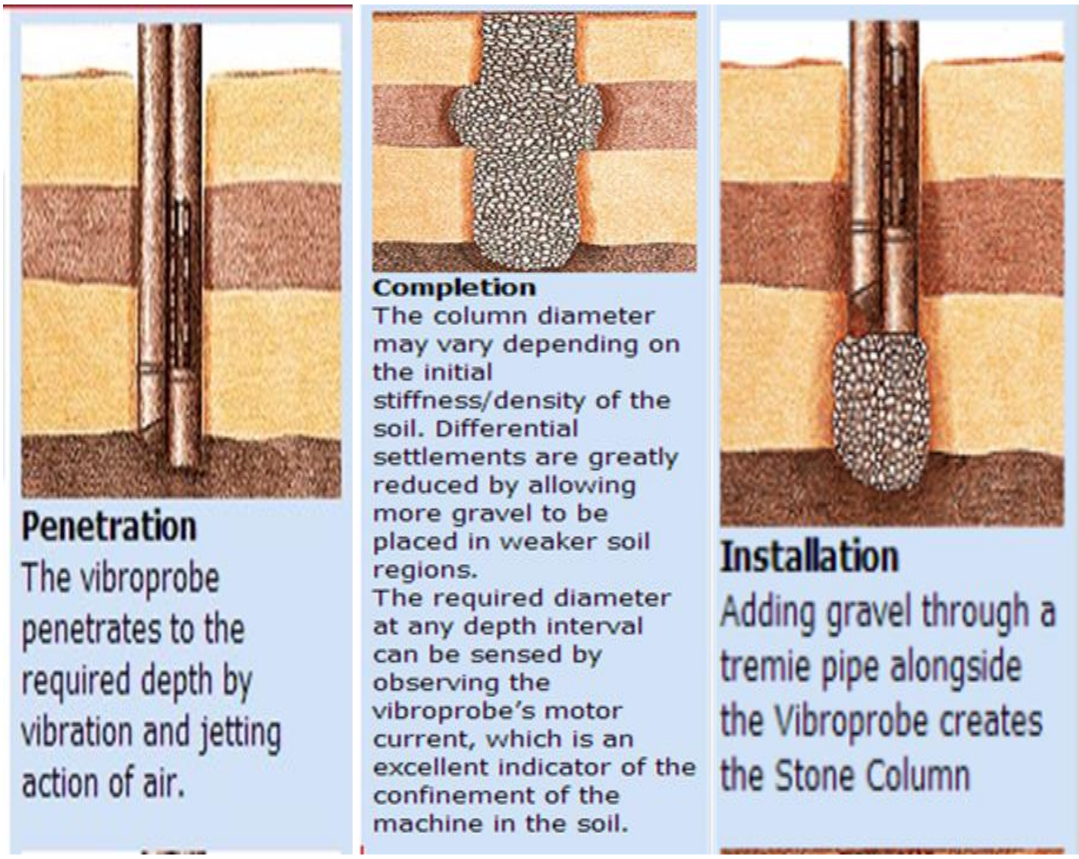

Fig. 1.4 Dry bottom feed method

1.2.3 Suitable Soils

The soil which does not react to vibration is considered good for stone column. They are clays, silts, silty and clayey sands, very fine sands and some of layered soils. The usefulness of stone columns for different type of soils is given in Table 1.1.

Table 1.1 Expected vibro-replacement stone column results

Ground type	Relative effectiveness	
	Densification	Reinforcement
Sands	excellent	very good
silty sands	very good	very good
non plastic silts	Good	Excellent
Clays	marginal	Excellent
mine spoils	excellent depending on gradation	Good
dumped fill	Good	Good
Garbage	not applicable	not applicable

1.2.4 Failure Mechanism of Stone Column

The major possible ways of failure of stone columns are :

- Bulging Failure
- Punching Failure
- General Shear Failure

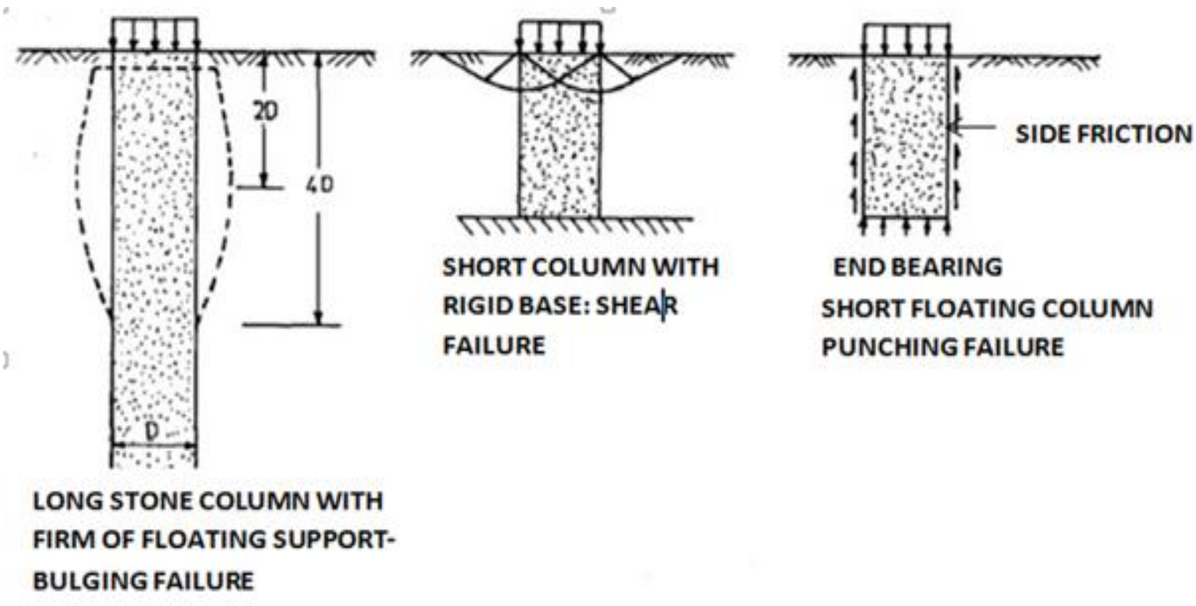

Fig. 1.5 Failure mechanism of stone column in homogenous soft layer (Barksdale and Bachus 1983)

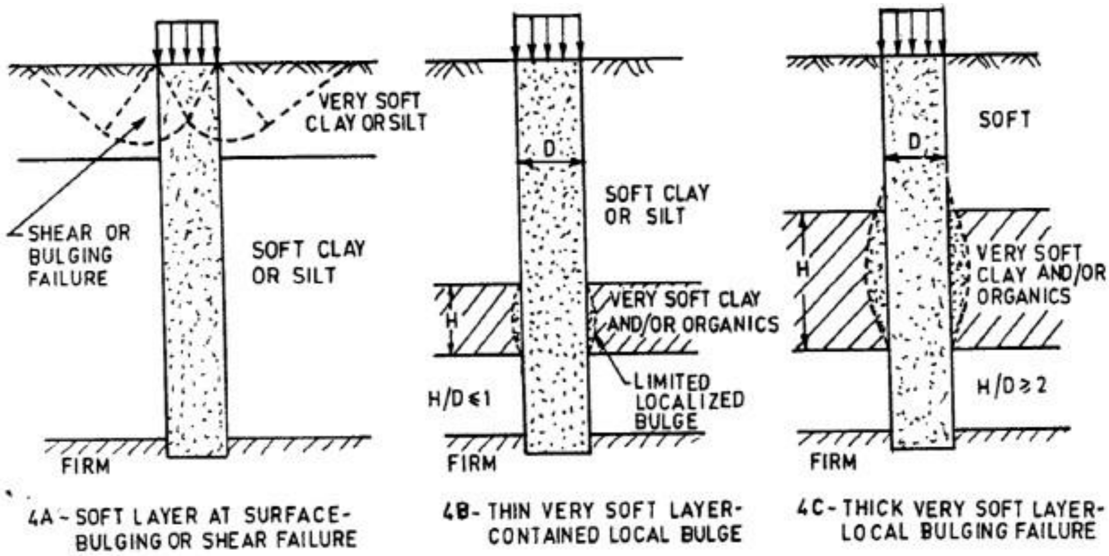

Fig. 1.6 Failure mechanism of stone column in non-homogenous soft layer (Barksdale and Bachus 1983)

CHAPTER 2

LITERATURE STUDY

2.1 INTRODUCTION

Main aim of inserting a stone column is to replace a percentage of the soft clay with stiffer granular material so that it could tolerate the load of the structure. Stone column derives its load carrying capacity from the confinement offered by the surrounding soil. In compression, stone column fails in different modes, such as bulging failure (Hughes and Withers 1974; Hughes 1976), general shear failure (Madhav and Vitkar 1978), pile failure or failure by sliding (Aboshi et al. 1979). Stone columns having a longer length than its critical length (i.e. about 4 times the diameter of the stone column) fails by bulging irrespective that it is end bearing or floating type (IS 2003). Depth of bulging zone of stone column is affected by column diameter rather than depth ratio and strength of soil (Bae et al. 2002). The depth of bulging is observed to be four times the diameter of the columns (IS: 15284-2003, Hughes and Withers 1974). Columns longer than critical length does not show further increase in load-carrying capacity however, longer columns may be needed to control the settlement (Babu et al.). Load carrying capacity of the stone column increases due to encasement and increase in load capacity depends on the modulus of encasement and the diameter of the stone column **(**Murugesan and Rajagopal 2010). Sharma et al. (2012) performed tests on stone columns by providing reinforcement in the form of horizontal strips of geosynthetic at different spacing over different column length and as encasement over the full column length.

2.2 BEHAVIOR OF STONE COLUMN

Different researchers have dealt with stone columns. These works primarily focus on evaluation of load carrying capacity and settlement analysis of soft soil reinforced with stone columns. All these works can be assembled under the these sub headings:

- Analytical and Numerical Studies.
- Theoretical Studies.
- Model Test Studies.
- Prototype/ Field Tests Studies.

2.2.1 Analytical and Numerical Studies:

Ambily and Gandhi (2006) studied the actual stress intensity on the stone column and soil using Finite Element Analysis (PLAXIS). Sand pad is provided at the surface to drainage and the impact of thickness of sand pad on load sharing between stone column and soil is analyzed by the analysis for both rigid and flexible loading condition.

Castro and Sagaseta (2011) studied an analytical solution in which the soft soil is dealt as an elastic material and the stone columns as elasto-plastic material using the Mohr-Coulomb model with a constant dilation angle. An elasto-plastic behavior is also considered for the circumferential encasement. The result outcomes are found in agreement with numerical analysis.

Indraratna et al. (2013) presented an analytical and numerical solution for ascertaining the performance of stone column reinforced in soil on the basis of the equal strain theory. To analyze the response of stone columns reinforced in soft soil under embankment loading, finite difference method is used by adopting free strain approach. They have considered both arching and clogging effect. The dissipation of excess pore water pressure is predicted by the proposed model. The resulting consolidation settlement with time is also determined.

Kaliakin et al. (2012) determined the results from analysis of 3-D finite element analysis. These analysis are done to simulate the behavior of geosynthetic encased stone columns in soft clay. Also a proportional study is performed to simulate the behavior of denser and granular soil within the encasement.

Khabbazian et al. (2011) also conducted three dimensional finite element analysis to geosynthetic encased columns in soft clay using three common functional form of the hyperbolic model for the encased granular material.

Malarvizhi and Ilamaruthi (2008) carried out triaxial tests by numerical analysis or finite element analysis on encased stone column using appropriate material models. The geogrid is modelled by using geogrid element and Mohr-Coulomb model is used for stone columns material. The stress-strain behavior of the geogrid encased stone columns is evaluated from finite element analysis and compared with the experimentally obtained values.

Mandal and Dutta (2012) performed axis-symmetric finite element analysis using finite element computer software PLAXIS 2D on end bearing stone columns with and without geogrid encasements. Variation in axial stiffness and length of encasement is done to analyze their effects on the behaviour of reinforced soft clay foundation. The results show that load carrying capacity increases as the encasement length increases. Also as the stiffness of the encasement material increases the performance of the encased stone column increases.

Marto et al. (2013) carried out finite element analysis to simulate the behavior of common stone column and encased stone column by geogrid in soft soil and presented the assumptions, procedures and results of the analysis. Load carrying capacity and settlement of simple stone column and geogrid encased stone column are compared with varrying diameter of stone columns.

Pulko et al. (2011) developed an analytical model, in which stone column is considered as an elasto-plastic material with constant dilatancy, soil as an elastic material and encasement material as a linear elastic material. The result show the influence of defferent parameters and provides a method for rational prediction of settlement for different encasement stiffness, load levels and column arrangements.

2.2.2 Theoretical Studies:

Deb et al. (2010) performed a mechanical model to predict the behavior of geo-synthetic reinforced granular fill resting over soft clay. The improved group of stone columns subjected to circular or axis-symmetric loading in which saturated soft clay, granular fills, geo-synthetic reinforcement and stone column are idealized by spring - dashpot system, Pasternak shear layer, rough elastic membrane and stiffer springs respectively. The results obtained by the mechanical model are compared with the laboratory model tests results.

Deb et al. (2012) developed an evolutionary genetic procedure NSGA (Non-dominated Sorted Genetic Algorithm) to analyze the stability of geo-synthetic reinforced embankments resting on stone columns and used this to locate the critical surface of embankments and to optimize the corresponding factor of safety of embankments under different conditions.

Mokhtari and Kalantari (2012) shows a key note on the installation method, design procedure and different failure modes of stone columns.

Rao et al. (2013) presented all the developments prepared on the use of granular anchored pile footing installed in expansive soils in terms of their efficiency in controlling the swell and shrink behavior of footings resting on these soils. Possible use of geo-synthetic encasement to granular pile is discussed here.

Tandel et al. (2012) discussed the key consideration for the general use of encased stone column, insights for design and construction and compiled the latest research developments. It is found that the performance of encased stone column of smaller diameter is superior to the larger diameter of stone columns for the same encasement.

Zhang et al. (2012) developed a theoretical solution for calculating the consolidation of foundations reinforced by geo-synthetic encased stone columns. The influence of geo-synthetics on the consolidation of composite foundation is analysed.

2.2.3 Model Tests Studies:

Ambily and Gandhi (2007) performed an experimental study on behavior of single stone column and group of seven stone columns by varying the parameters like spacing between the stone columns, shearing strength of soft soil and loading condition. Finite Element Analysis (PLAXIS-2D) is also analysed using 15-noded triangular elements and obtained results are compared with the experimental results.

Ayothiraman and Soumya (2011) are used shredded waste tyre chips as an alternative material to stone aggregates in construction of stone columns. From the experimental results, it is said that chips of waste tyre can be used as partial replacement of stone chips up to about 60% in stone columns.

Beena and Shukoor (2012) have studied the behaviour of stone columns in which a portion of the stone aggregates is replaced by locally available material rice husk. Stone column provides a drainage path to the water confined in the clay and rice husk degrades the consolidation of clay. From experimental results, it concluded that partial replacement of stone chips with locally available rice husk does not affect the performance of stone columns.

Deb et al.(2011) presented the results from a series of laboratory model tests on common sand bed and geogrid reinforced sand bed resting on stone columns improved soft clay. It is observed that load carrying capacity of soil increases due to the placement of sand bed over the stone column and bulging diameter of stone columns reduces as the depth of bulge increases.

Gniel and Bouazza (2009) had discussed a series of model tests conducted to examine the behaviour of geogrid encased stone columns. Length of encasement is varied to see the behavior of different partial encased stone column and fully encased stone column. It is obtained that in case of partial length of encasement to the stone column, there is a fixed reduction in vertical strain occurs due to increase in length of encasement for both single and group of stone columns. For a full length of encasement, there is an increment in column stiffness and reduction in column strain.

Isaac and Girish(2009) studied the reinforced stone column using five different reinforcement materials like stone chips, river sand, gravels, sea sand and quarry dust. And the load-settlement response is obtained. From experiment, it is obtained that there is no substantial difference in the load-settlement behavior of stone columns for river sand and sea sand. A Finite element analysis is also performed using computer software PLAXIS-2D.

Murty et al. (2011) showed the results from experimental tests conducted on reinforced marine clay with stone columns in the laboratory when subjected to cyclic load. Unit cell concept is adopted to test the single stone column. The behavior of stone columns is studied by applying the static load and cyclic load.

Murugesan and Rajagopal (2010) did the experimental tests on the qualitative and quantitative improvement of load carrying capacity of an encased stone column. Load tests are done on both single and group of stone columns both without encasement and with encasement. And it was found that ultimate load carrying capacity of stone columns increases with encasement. The increment in load carrying capacity depends on the modulus of encased material and the diameter of the stone columns.

Najjar et al. (2010) obtained the improvement of mechanical properties of soft clay using sand columns. The height of sand column, type of sand column (encased, non-encased) and confining pressure is varied. Test results showed that sand columns improve the undrained strength of soft soils.

Raju et al. (2012) observed experimentally the load-settlement response of stone column and geotextile encased stone column. Load tests are performed on expansive soil stabilized with four stone columns arranged in square pattern with and without encasement for different L/D and S/D ratios. The settlement in encased stone column is less than normal stone column and it decreases with increasing stiffness of the encased material.

Sharma and Phanikumar (2005) showed the bulging behavior of expansive soil reinforced with geo-piles that are vertical cylindrical holes made of geogrid. Effect of diameter of the geopile and types of filling material on the heave was studied. And it was found that the heave decreases with the increased diameter of geopile and grain size of filling materials. For group of geopiles, spacing between geopile was varied and it showed that the heave decreases for less spacing of geopiles.

Sharma et al. (2012) studied stone columns with internal reinforcement in the form of horizontal strips at different spacing. And it was found that full length encasement gives high load carrying capacity as compared to the partial encasement over the top portion of stone column for both type of stone columns floating and end bearing. And it was found that the best arrangement of horizontal strips was the placement of the strips over full length of stone column at d/2 spacing.

2.2.4 Prototype / Field Tests Studies:

Lee et al. (2008) studied the increment in the ultimate load capacity and reduction in bulging of a geogrid encased stone column using field load tests. It was observed from the field experiment that encased stone columns have much higher load carrying capacity and lesser lateral bulging compared to normal stone columns.

Poorooshasb and Meyerhof (1997) investigated the efficiency of general stone columns and lime columns in reduction in settlement of soft soils. The effect of several factors like column spacing, properties of soil, properties of stone chips, in situ stress and the depth of firm base from the tip of the column was studied.

CHAPTER 3

THEORY AND METHODOLOGY

3.1 INTRODUCTION

The marine soil, compressible soil, pit deposits etc. are characterized by its very low bearing capacity and high compressibility, making them unsuitable for any type of civil engineering construction. For any construction activity over these type of soils needs a proper understanding of the mechanical properties of these deposits and also the suitability of any ground improvement techniques that can be adopted. One common method to treat these type of soils is the installation of stone columns.

When stone columns are installed in exceptionally soft soils, the lateral confinement offered by the surrounding soil may not be adequate to form the stone column, and the bulging of stone column will be more, which will be lead to larger surface settlements. This is the major limitation of the stone column technique, especially in very soft soils. One method to improve the performance of stone columns installed in soft soils is wrapping the general stone column with a suitable geosynthetic in a tubular form. This type of encasement by a geogrid or geotextile imparts additional lateral confinement and makes the stone columns stiffer and stronger. In addition, when the stone columns are encased in geosynthetic, it promotes the vertical drainage function of stone column by acting as a good filter. Filter means it prevent fines from mixing with the stone column materials. Expansion of stone column material causes the lateral bulging, which will induce a hoop tension force in the encasement and developed additional confinement. These additional confining stress increases the bearing capacity of stone column and decreases the rate of settlement.

In present study, computer finite element program PLAXIS2D is used to analyze the behavior of stone columns with and without encasement.

3.2 FINITE ELEMENT ANALYSIS

The analysis was carried out using an available finite element package PLAXIS-2D. The finite element program can be used in axisymmetric modelling as well as plain strain modelling. An axisymmetric analysis was carried out using Mohr-Coulomb's criterion considering elasto-plastic behaviour for soft clay and stone. The finite-element discretization (meshing) was done using 15-noded triangular elements and basic boundary conditions used to represent the stone column and surrounding clay as shown in fig. 3.1. The diameter of tank is considered 10 times the loading area. Along the periphery or vertical boundary radial deformation is restricted where settlement is allowed but along the bottom both radial deformation and settlement are restricted. At the interface between the stone column and soft clay, no interface elements have been used as the deformation of the column is mainly by radial bulging and no significant shear is possible. Also the interface between a stone column and clay is a mixed zone where the shear strength properties can vary depending on the method of installation. As the method of installation is not precisely known, an interface element is not used. Mitchell and Huber (1985), Saha et al. (2000), Ambily and Gandhi (2007), etc., also carried out a similar finite-element analysis of a stone column without an interface element.

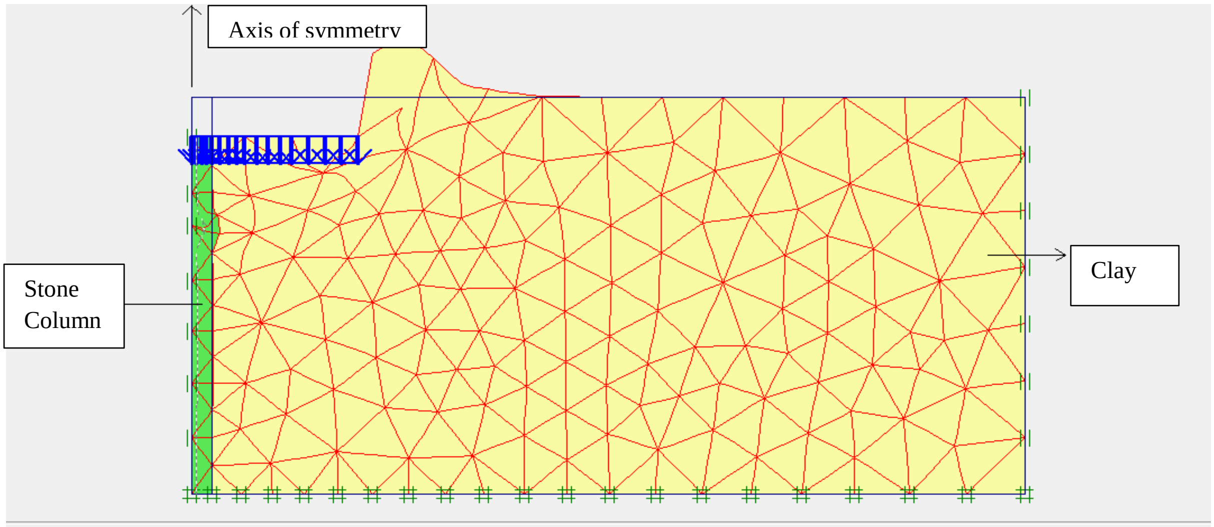

Fig. 3.1 A typical finite element mesh

3.3 MATERIAL USED

The Mohr-coulomb analysis requires a total of six parameters. These parameters are Young's modulus (E), dry unit weight (γ_d), Poisson's ratio (μ), angle of internal friction (φ), unit undrained cohesion (c_u) and dilantancy angle (ψ). The input parameters (E, μ, φ, ψ, $c_{u,}$ γ_d) are given in Table 1 taken from Ambily and Gandhi (2007). In present study, the water table has been set to be at the end of the clay deposit. A drained behaviour is assumed for for all the materials. In this analysis, it is assumed that sufficient time has lapsed after applying the load and stress concentration and settlement has been stabilized.

Table 3.1 Properties of materials used

Material	W (%)	E (kPa)	μ	c_u (kPa)	Ψ (deg)	Φ (deg)	γ_d (kN/m^3)	γ_{sat} (kN/m^3)
Clay	25	5500	0.42	30	-	-	15.56	19.45
	30	3100	0.45	14	-	-	14.60	18.98
	35	2150	0.47	7	-	-	13.60	18.38
Stone	-	55000	0.30	-	10°	44°	16.62	-

The geogrid is modelled as elasto-plastic continuum element whose axial stiffness is taken as the secant modulus, obtained from the tension test. The tensile modulus (EA) of geogrids (ratio of the axial force per unit width and the axial strain) and the yield strength (N_p) are used to define the elasto-plastic behavior of geogrid. Idealized elasto-plastic behavior of geogrid is indicated as dotted line in Fig. 3.2. A typical load-strain curve of the geogrid material is shown in Fig. 3.2. From the load-strain data, tensile modulus (EA) is obtained for the strain level of 6% and its yield strength (N_p) is taken as 1.2 kN/m at 10% strain level.

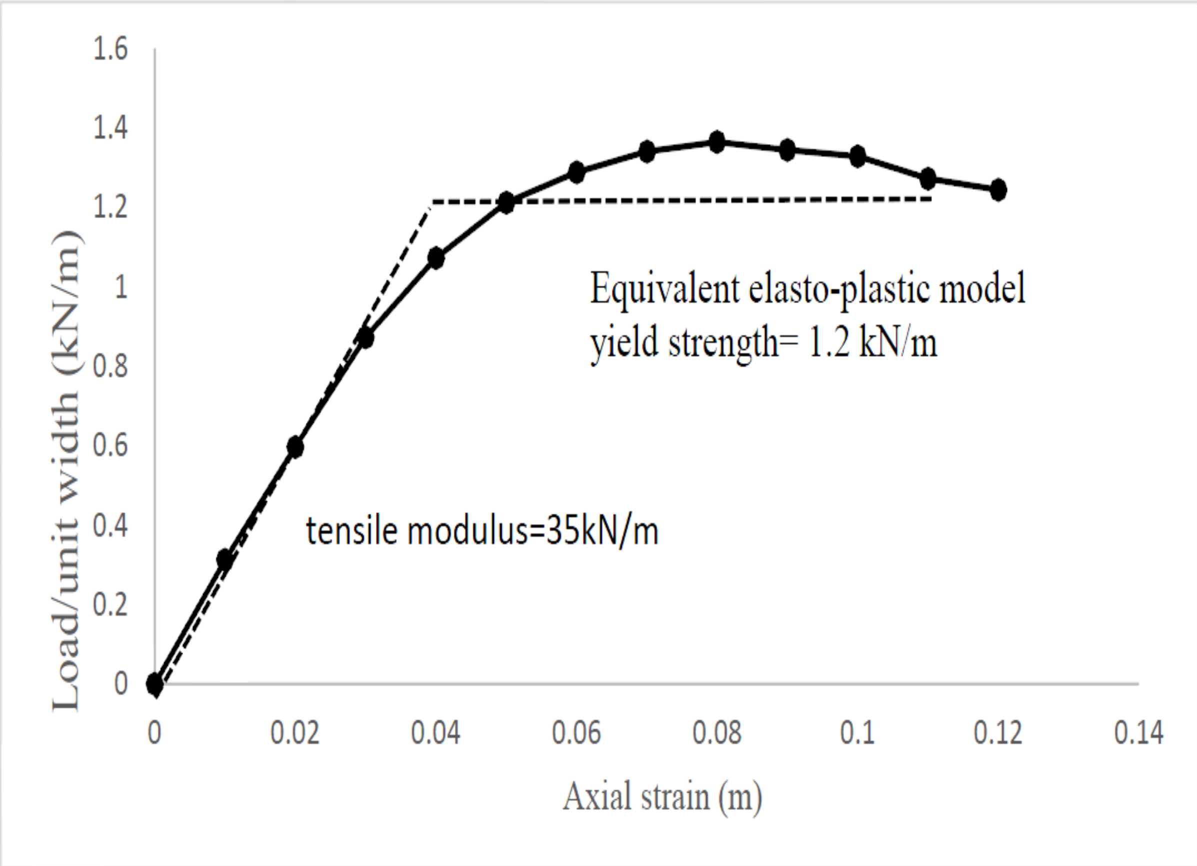

Fig. 3.2 Tensile test on the geogrid

3.4 TEST-1: EFFECT OF DIAMETER RATIO

Diameter ratio is the ratio of diameter of loading area to that of stone column. With variation in diameter ratio there are variations in parameters of stone columns. Thus a complete model of stone column is built to analyse the effect of diameter ratio on:

a) Ultimate strength of stone column
b) Depth of maximum bulging
c) Diameter of maximum bulging.

A schematic view of loading plan on a stone column confined by soft clay is shown in Fig.

3.3.

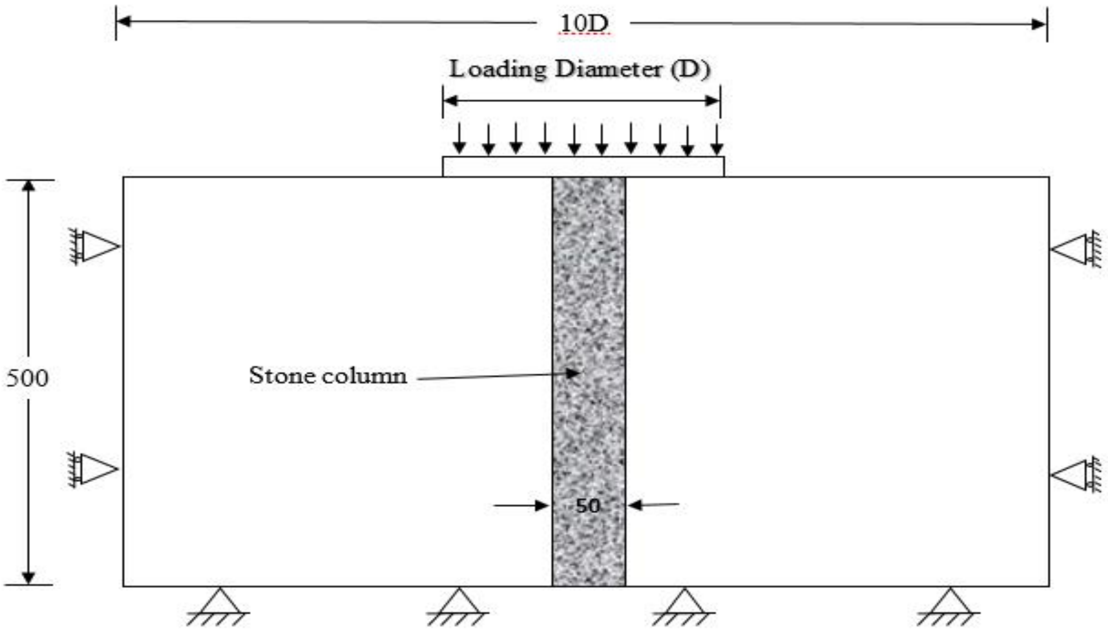

Fig 3.3 A schematic view of loading plan

3.5 TEST-2: EFFECT OF LENGTH OF CIRCUMFERENTIAL ENCASEMENT

When stone columns are installed in extremely soft soils, the lateral confinement offered by the surrounding soil may not be adequate to form the stone column. One method to improve the performance of stone columns installed in soft soils is wrapping the general stone column externally with a suitable geosynthetic in a tubular form. This type of encasement by a geogrid or geotextile imparts additional lateral confinement and makes the stone columns stiffer and stronger. Thus a complete model of stone column is built to analyze the effect of circumferential encasement on:

a) Ultimate strength of stone column

b) Position of bulging

A schematic view of loading plan on an encased stone column confined by soft clay is shown in Fig. 3.4.

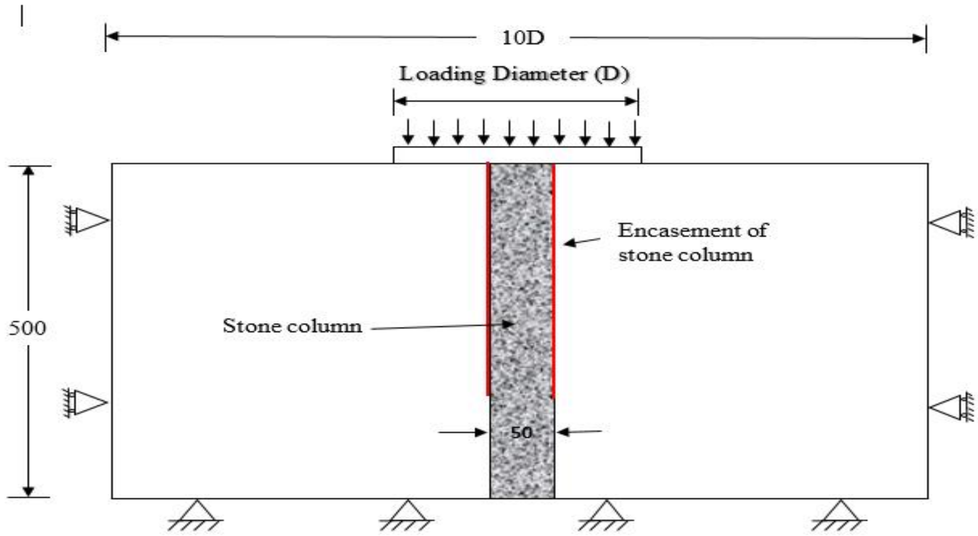

Fig. 3.4 A schematic view of loading plan of encased stone column

Firstly, an encasement of length 2D is applied on upper portion of stone column as stone column fails due to bulging and bulging appears in upper portion of stone column. Then encasement depth is increased to 4D, 6D, 8D and 10D. The load-settlement curve for different strength of confinement material is analyzed by providing 100% strain with respect to diameter of stone column (D).

3.6 TEST-3: EFFECT OF HORIZONTAL CIRCULAR STRIP

Another method of improving the performance of stone columns is by providing horizontal circular strips internally at regular interval to restrict the bulging. Thus a complete model of stone column is built to analyze the effect of horizontal circular strip on ultimate strength of stone column. A schematic view of loading plan of a stone column with horizontal circular strips confined by soft clay is shown in Fig. 3.5.

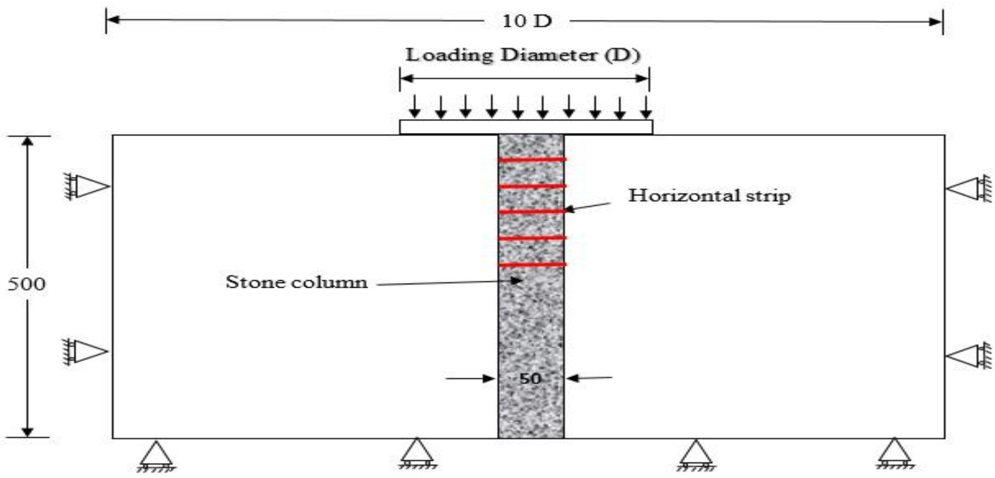

Fig. 3.5 A schematic view of loading plan of stone column with horizontal circular strips

3.7 TEST-4: EFFECT OF HORIZONTAL CIRCULAR STRIP ON ENCASED STONE COLUMN

In order to enhance the performance of stone column, a combination external reinforcement and internal reinforcement is considered. A schematic view of loading plan of an encased stone column with horizontal circular strips confined by soft clay is shown in Fig. 3.6.

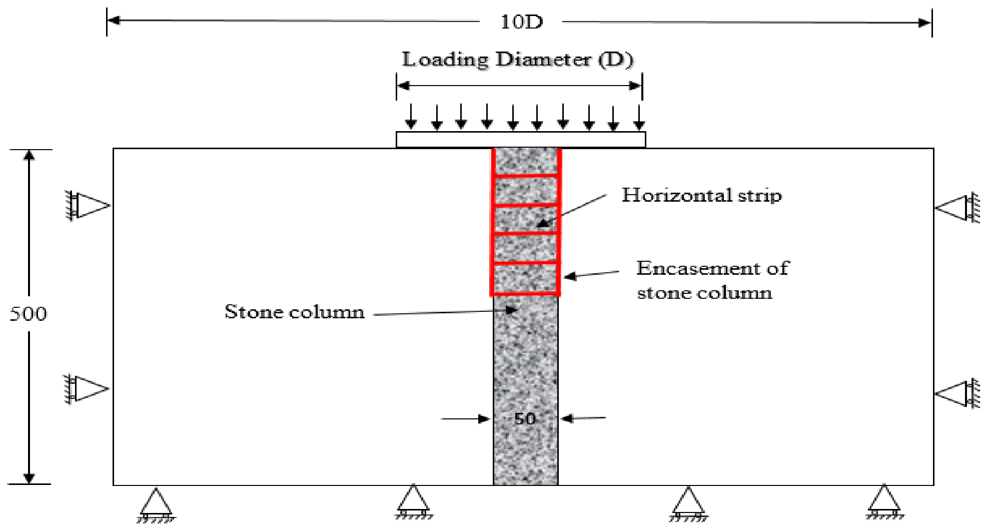

Fig. 3.6 A schematic view of loading plan of encased stone column with horizontal circular strips

CHAPTER 4
RESULT AND DISCUSSION

4.1 INTRODUCTION

Stone columns derives its load carrying capacity from the confinement offered by the surrounding soil. Encasement of stone column has been extended the use of stone columns to soft clays. The present study contains stone column with three type of extra confinement circumferential encasement, circular horizontal strips and combination of two. An axisymmetric analysis was carried out using Mohr-Coulomb's criterion considering elasto-plastic behaviour for soft clay and stone. Three type of surrounding is considered 7, 14, 30 kPa and the load carrying capacity of footings located over stone columns is compared with equal size of footings located on the virgin soil that is without a stone column underneath.

4.2 RESULT OF TEST-1

The complete model of stone column to analyze the effect of diameter ratio on various parameters is shown in section 3.3.

4.2.1 Effect of Diameter Ratio on Ultimate Strength

By changing the diameter ratio (ratio of diameter of loading area and diameter of stone column), the change in the ultimate strength is observed for the different strength of the confining material. Fig. 4.1 shows the relation between the diameter ratios to ultimate strength for the different shear strength (c_u = 7kPa, 14kPa and 30kPa) of confining soil. From the figure, it is clear that there is a little improvement in ultimate strength of loaded area after diameter ratio of 5. Table 4.1 shows the ultimate strength and the percentage increment in maximum strength for different diameter ratio for different confinement shear stress c_u.

There is 10 % increment in ultimate stress for diameter ratio of 6 with respect to virgin clay but it can be increased up to 100 % by preventing the bulging by any means i.e. by providing geosynthetic encasement or geogrid horizontal strip.

Table 4.1 Effect of diameter ratio on ultimate strength of stone column for different c_u

Diameter Ratio (Dr)	Cu=7 kPa		Cu=14 kPa		Cu=30 kPa	
	Ultimate Strength (kN/m^2)	Increment in Strength (%)	Ultimate Strength (kN/m^2)	Increment in Strength (%)	Ultimate Strength (kN/m^2)	Increment in Strength (%)
1	208	365	397	346	816	332
2	86.4	93	167.2	88	348	84
3	63.3	41.6	124.1	39.4	261	38
4	54.4	21.7	107.6	21	227	20
5	51.2	14.5	101.4	14	213.7	13
6	50.0	11.8	98.7	11	208.4	10
7	47.8	6.9	94.8	6.5	202	7
8	46.8	4.7	93.0	4.5	197.5	4.6

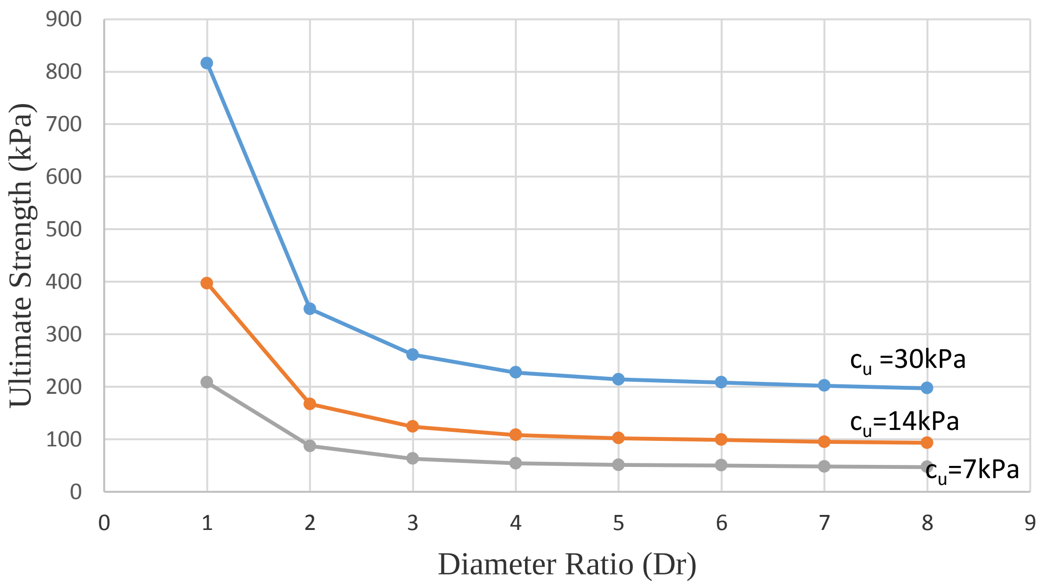

Fig. 4.1 Effect of diameter ratio and c_u on ultimate stress of stone column

4.2.2 Effect of Diameter Ratio on Depth of Maximum Bulging and Diameter of Bulging

Total depth of bulging increases with increase in diameter ratio as given in table 4.2. Total depth of bulging not only depend on diameter of stone column but also on the loading area i.e. critical length depends on the diameter of column along with the loading area. It is observed that with increase in diameter ratio, depth of maximum bulging diameter increases, by decreasing degree of bulging. Fig. 4.2 shows the variation of diameter of maximum bulging with diameter ratio for different shear strength of confined soil. For a particular diameter ratio depth of maximum bulging decreases with decrease in shear strength of surrounding clay.

Table 4.2 Effect of diameter ratio on depth and diameter of bulging for c_u =30 kPa

Diameter Ratio	Dia. of Maximum Bulging (mm)	Depth of Maximum Bulging (mm)	Total Bulging Depth (mm)
1	82	15	220
2	72	25	350
3	68	50	370
4	66	62	400
5	64	66	420
6	62	90	430
7	62	125	440
8	64	135	450

There is sharp bulging when diameter ratio is low but bulging is distributed along a larger length when diameter ratio is high i.e. a greater length should be protected to prevent the bulging when area ratio is high and a smaller should be protected when area ratio is low. In the present study it is found that when diameter ratio is greater than 3 then for low confining strength the diameter of maximum bulging is more than high confining strength as shown in fig. 4.3. But when diameter ratio is between the 1 to 3 then for low confining strength the diameter of maximum bulging is less than high confining strength.

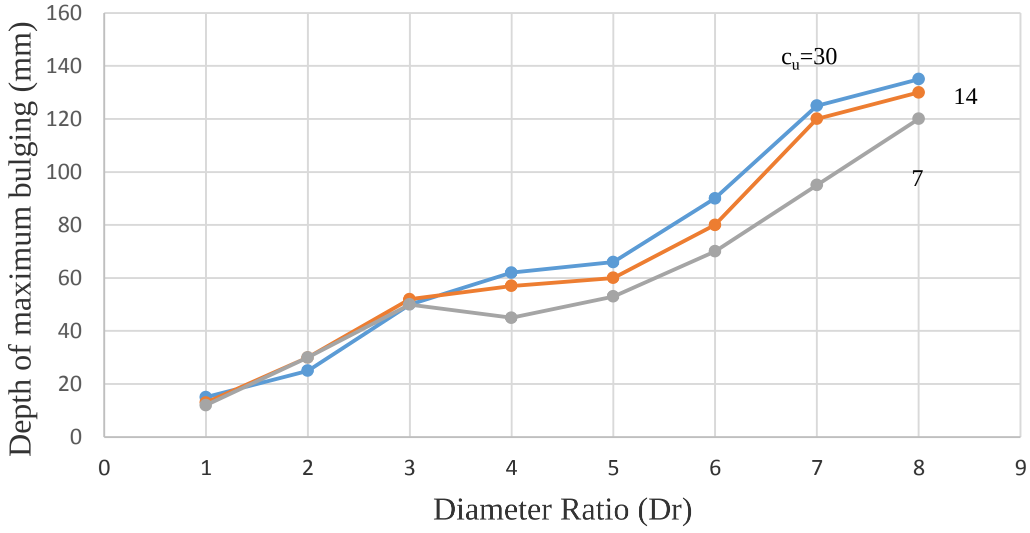

Fig. 4.2 Effect of diameter ratio on depth of maximum bulging for different c_u

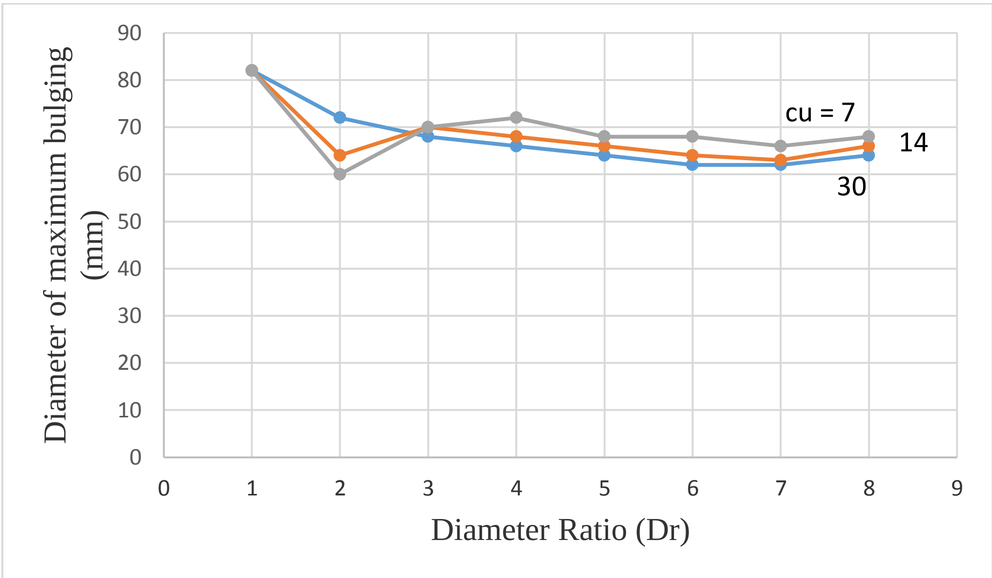

Fig. 4.3 Effect of diameter ratio on diameter of maximum bulging for different c_u

4.3 RESULTS OF TEST-2

The complete model of stone column to analyze the effect of circumferential encasement length on various parameters is shown in section 3.4.

4.3.1 Effect of length of encasement length on Ultimate Strength

The effect of length of encasement on ultimate strength of stone column is observed. The Geogrid encasement length is varied as 2D, 4D, 6D, 8D and 10D to see the effect of encasement length on ultimate strength of stone column (where D is diameter of stone column) which is shown in Fig 4.4.

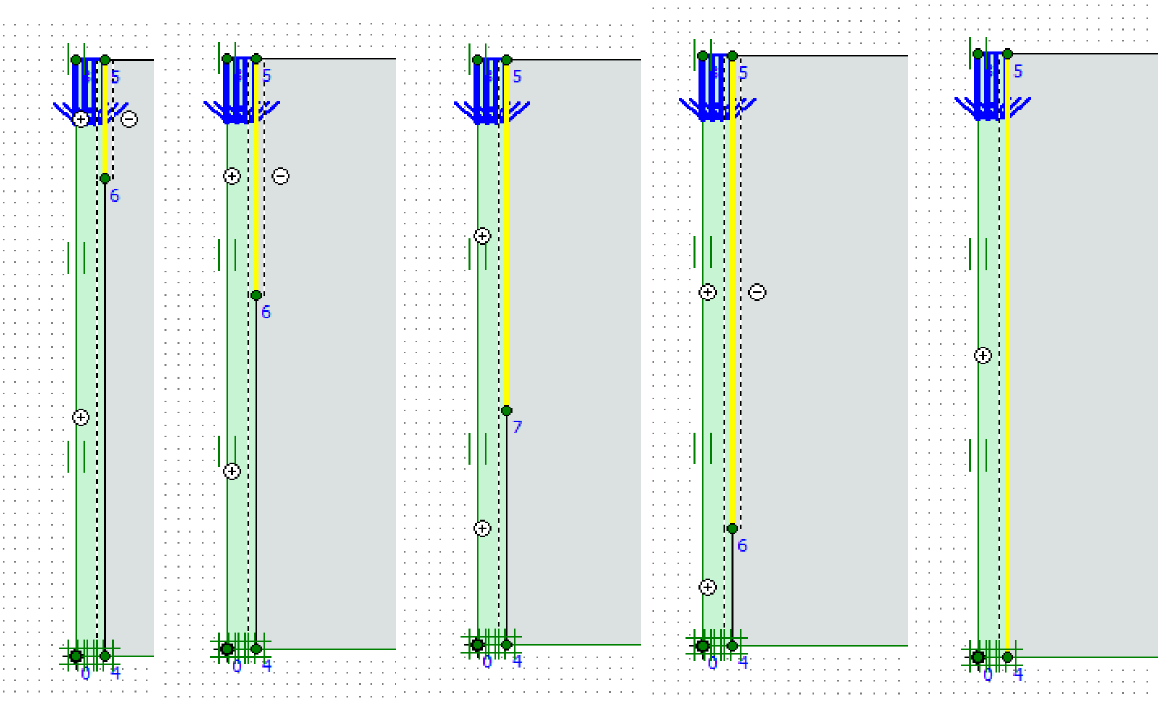

Fig. 4.4 Different geogrid encasement depth (2D, 4D, 6D, 8D, 10D) for stone column

Fig. 4.5 shows the load-settlement curve for different encasement length for confinement shear strength of material 7 kPa. From this figure, it is cleared that if encasement length increases the ultimate strength of stone column increases. Although, percentage of increase in ultimate strength decreases with increased encasement length.

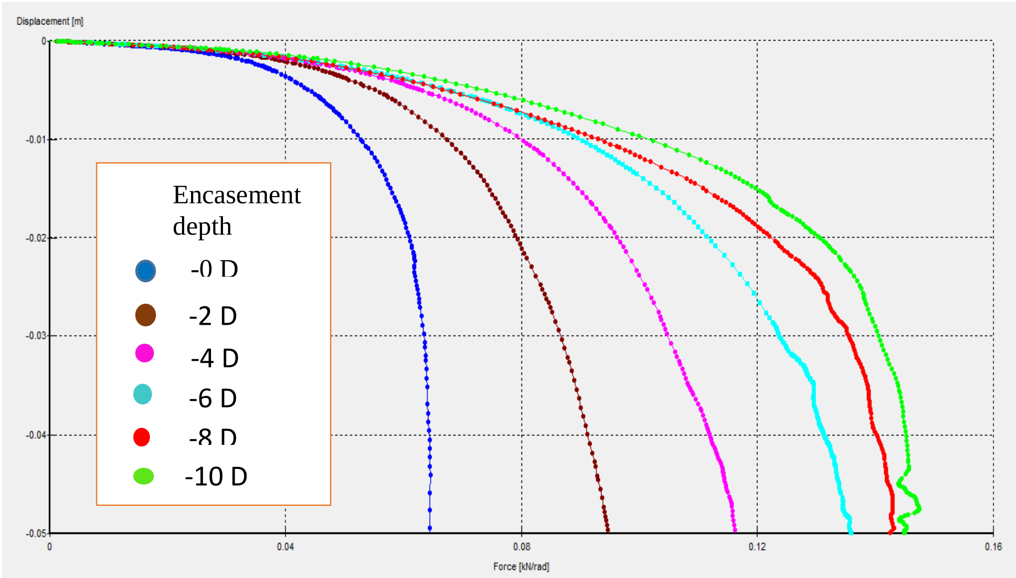

Fig. 4.5 Load settlement curve for different encasement depth for c_u= 7 kPa

Fig. 4.6 shows the load-settlement curve for different encasement depth for confinement strength of material 14 kPa. Here the change in ultimate strength is negligible after encasement length of 6D.

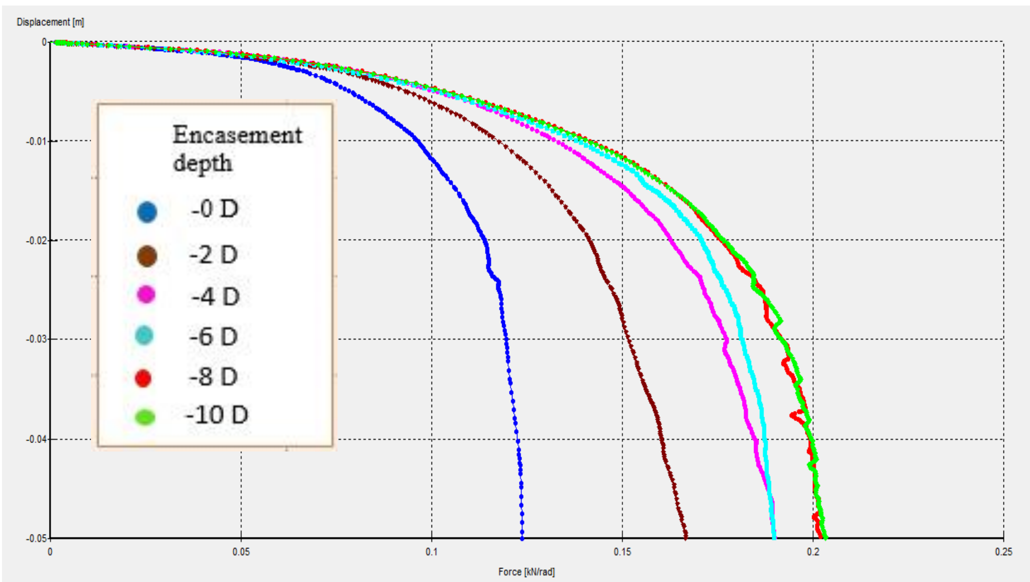

Fig. 4.6 Load settlement curve for different encasement depth for c_u= 14 kPa

Fig. 4.7 shows the load-settlement curve for different encasement length for confinement strength of material 30 kPa. From this figure, it is cleared there is no change in ultimate strength after encasement length of 4D.

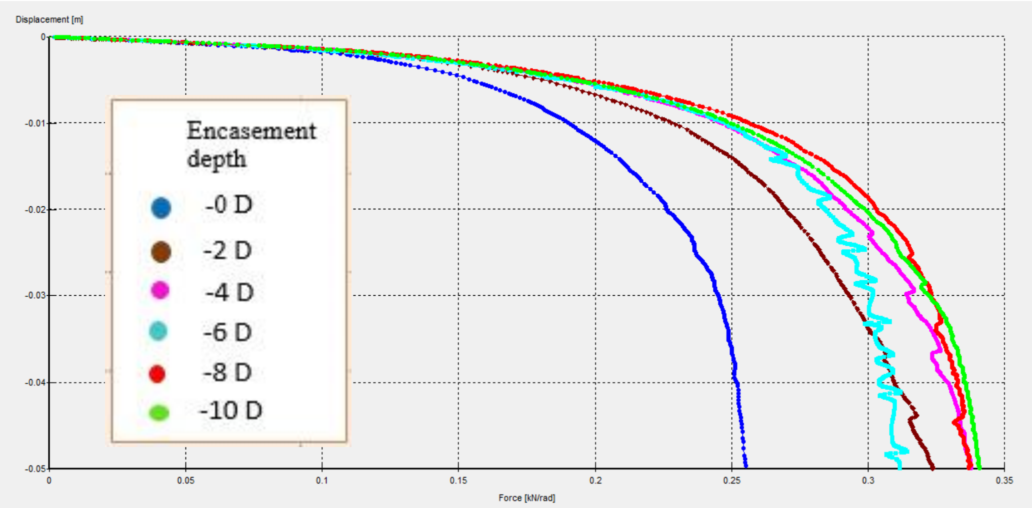

Fig. 4.7 Load settlement curve for different encasement depth for c_u= 30 kPa

Same analysis when done with diameter ratio (D_r) two, load-settlement curve for different encasement length for confining shear strength of material 7 kPa is shown Fig. 4.8. From this curve, it clear that change in ultimate strength is negligible after encasement length of 8D. but when diameter ratio was one then the increase in ultimate strength continues up to 10D.

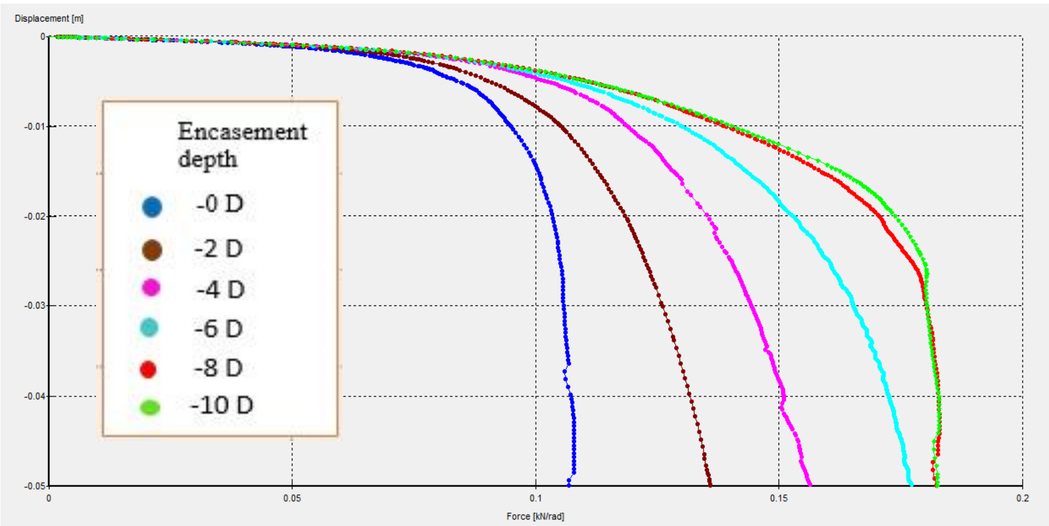

Fig. 4.8 Load settlement curve for D_r 2 for different encasement depth for c_u= 7 kPa

Fig. 4.9 shows the load settlement curve for different encasement length for diameter ratio 2 for confining shear strength of 14 kPa. This figure shows that, there is no significant increase in ultimate strength after the encasement length of 6D.

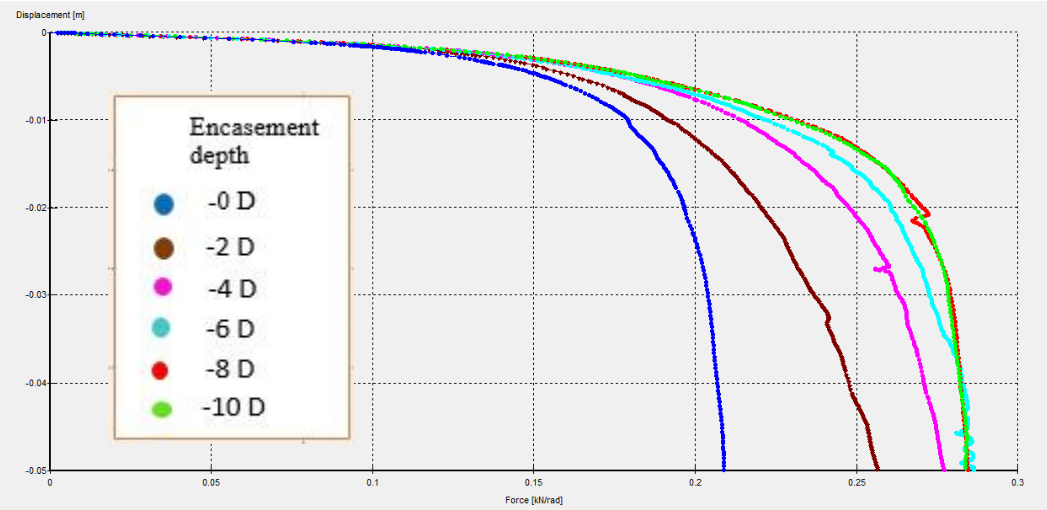

Fig. 4.9 Load settlement curve for D_r=2 for different encasement depth for c_u= 14 kPa

Fig. 4.10 shows the load settlement curve for different encasement length for diameter ratio 2 for confining shear strength of 14 kPa. This figure shows that, there is no significant increase in ultimate strength after the encasement length of 4D.

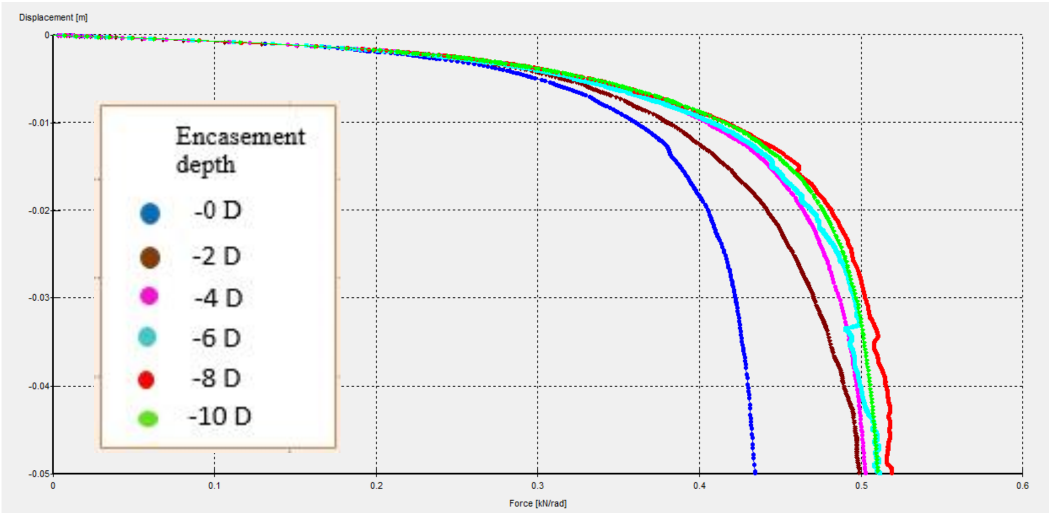

Fig. 4.10 Load settlement curve for D_r=2 for different encasement depth for c_u= 30 kPa

Fig. 4.11 shows the load-settlement curve for simple stone column and fully encased stone column for different confining shear strength of soil.

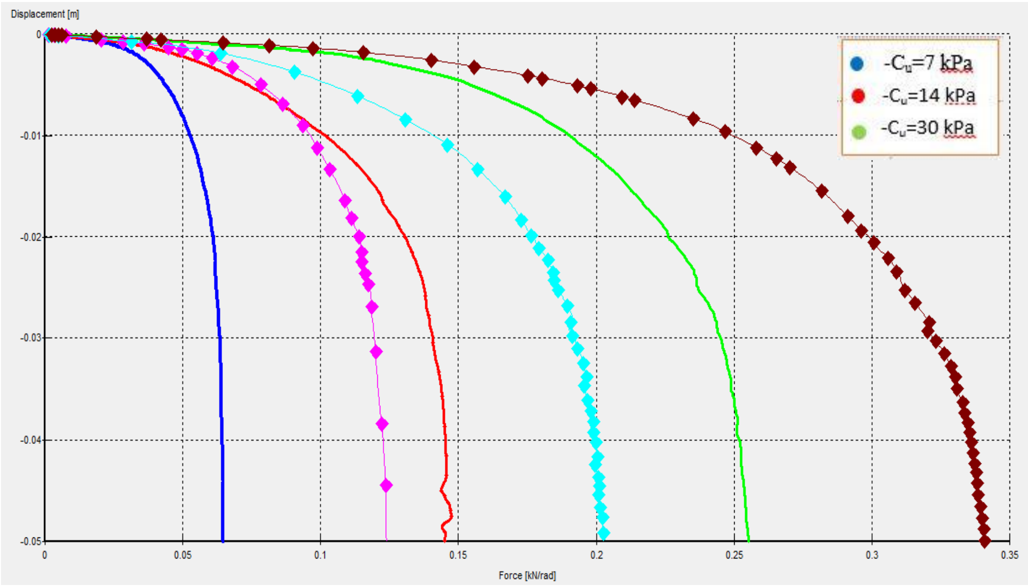

Fig. 4.11 Load settlement curve when only stone column loaded for simple stone column and fully encased stone column for different c_u

4.3.2 Effect of length of encasement length on Position of Bulging

The variation of position of bulging of stone column with the change in length of encasement is portrayed in Fig. 4.12, Fig. 4.13 and Fig. 4.14 for different confining shear strength of soil (c_u= 7,14 and 30 kPa). From figures, it is cleared that for low strength of soil i.e. 7kPa, the bulging of stone column occurs just below the length of encasement. For confining strength of soil c_u= 14kPa, there is no significant bulging below the encasement for the encasement length of 6D and above. However, for high shear strength of soil i.e. 30kPa (stiffer soil), bulging below the encasement for the encasement length of 4D and above is very negligible.

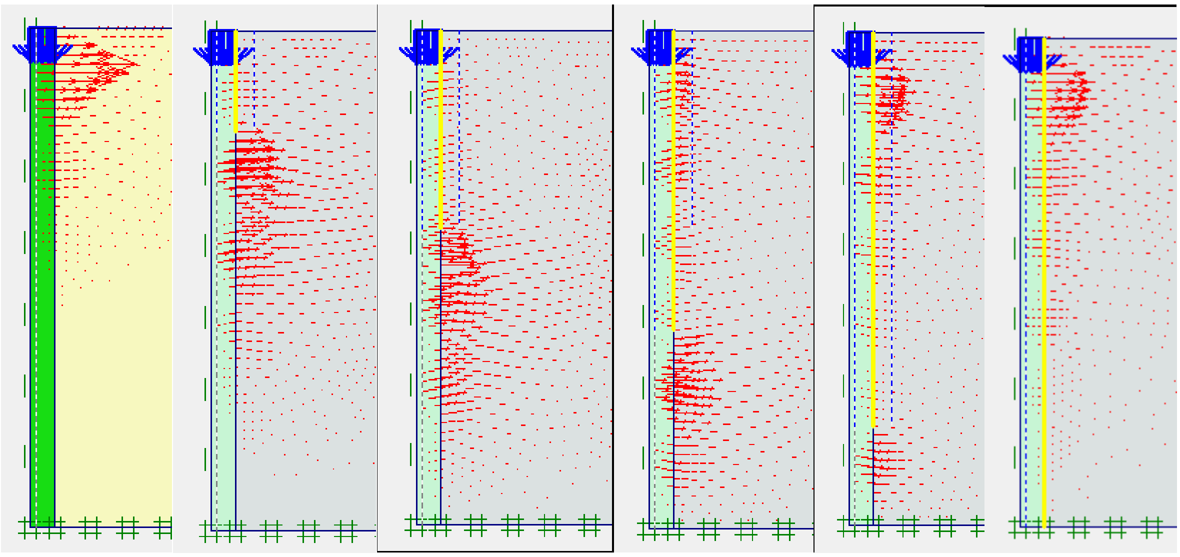

Fig. 4.12 Bulging of stone column for different encasement depth for c_u= 7kPa

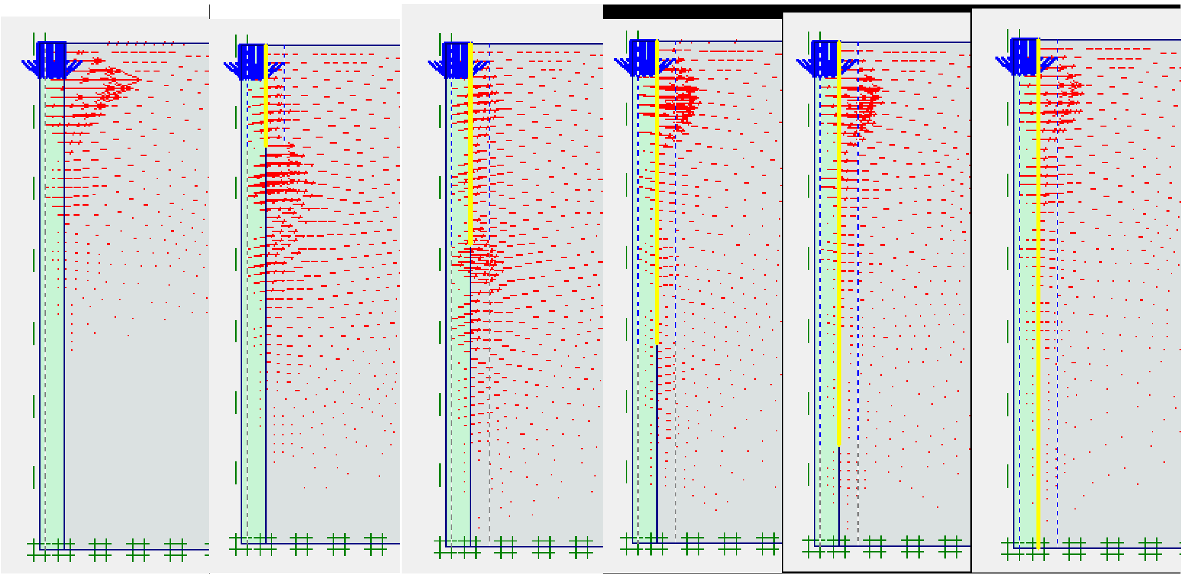

Fig. 4.13 Bulging of stone column for different encasement depth for c_u= 14kPa

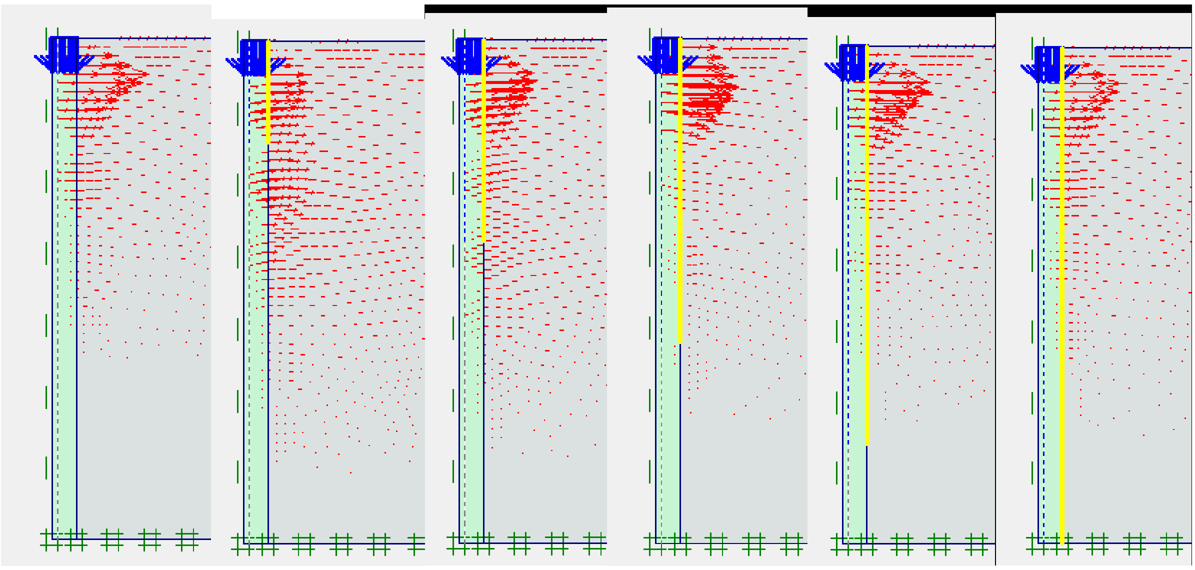

Fig. 4.14 Bulging of stone column for different encasement depth for c_u= 30kPa

4.4 RESULT OF TEST-3

The complete model of stone column to analyze the effect of horizontal circular strip on ultimate strength is shown in section 3.5.

4.4.1 Effect of Horizontal Circular Strip on Ultimate Strength

Different number of horizontal strips are provided in the stone column with a spacing of half of diameter of stone column. The load settlement curve for different number of horizontal strip on stone column varying from 1 to 6 has been analyzed. Fig. 4.15 shows curves of load settlement for c_u=7 kPa with various number of horizontal circular strips. There is significant increase in the ultimate strength of stone column with increase in number of horizontal circular strips. Fig. 4.16 shows the load settlement curve for c_u=14kPa with various number of horizontal circular strips. It is clearly visible that there is no significant increase in ultimate strength after 5 horizontal strips. However, in Fig. 4.17, which shows the load settlement curve for c_u=30kPa with various number of horizontal circular strips, the ultimate strength remains same for 3 or more number of horizontal circular strips.

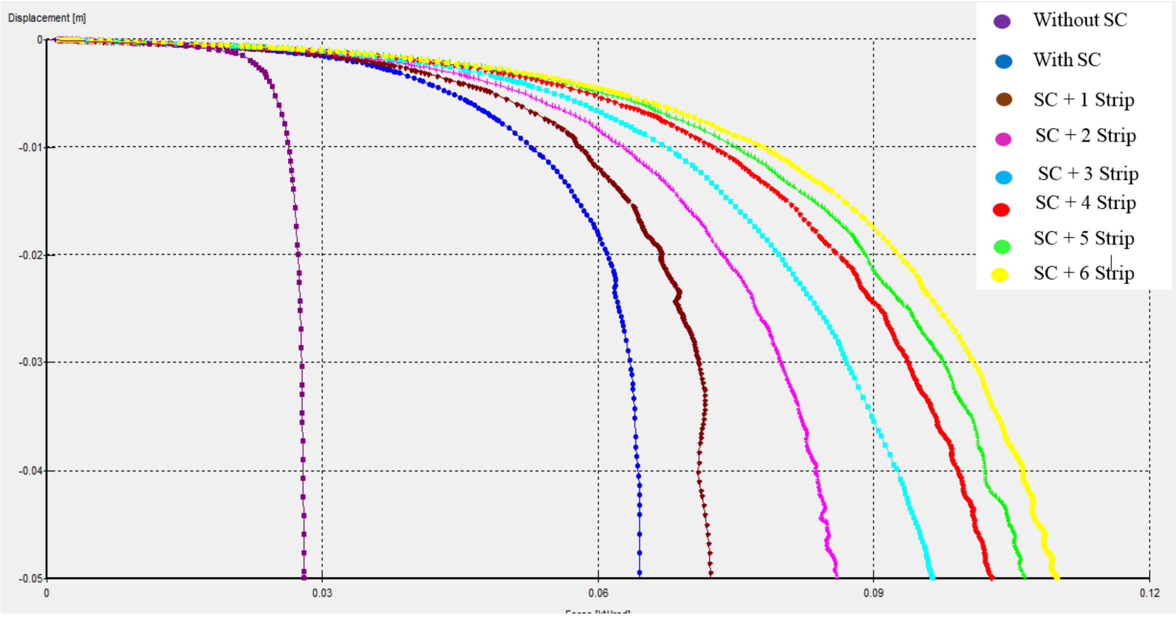

Fig. 4.15 Load settlement curve for different number of horizontal strips for c_u=7 kPa

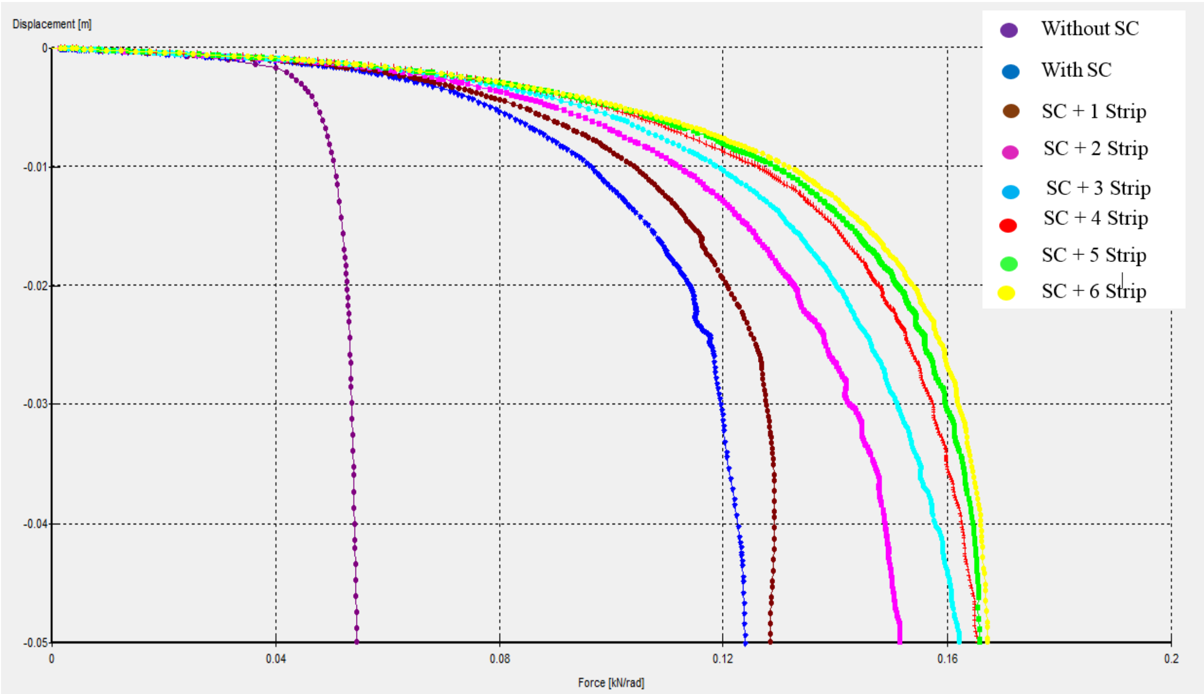

Fig. 4.16 Load settlement curve for different number of horizontal strips for c_u=14 kPa

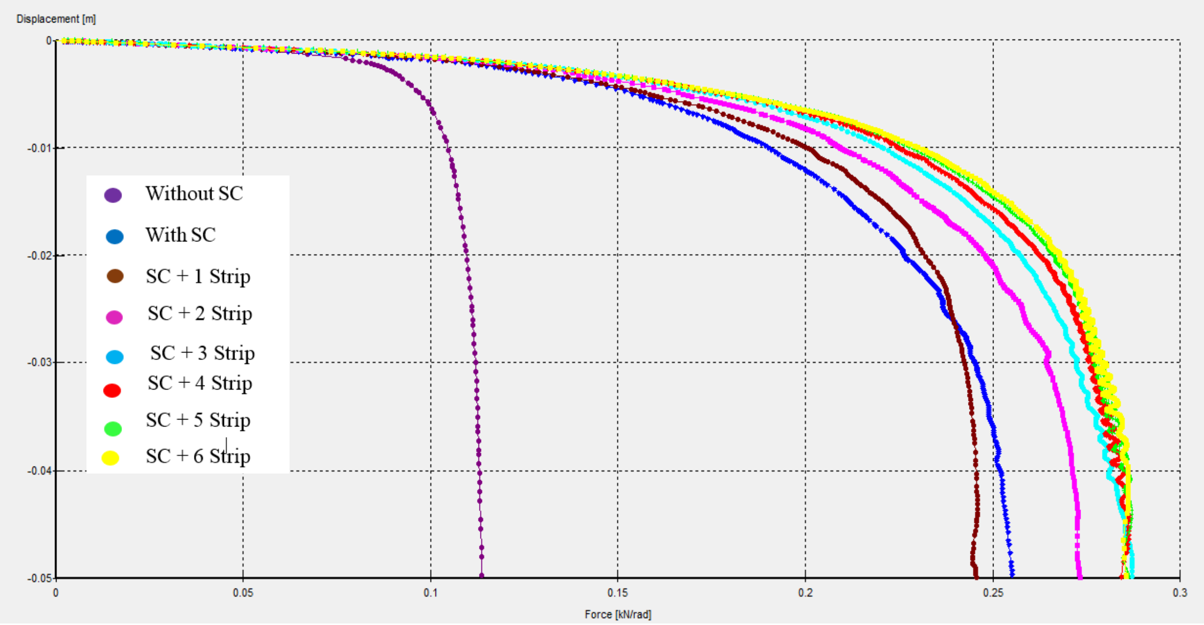

Fig. 4.17 Load settlement curve for different number of horizontal strips for c_u=30 kPa

4.5 RESULT OF TEST-4

The complete model of stone column to analyze the effect of combination of circumferential encasement and horizontal circular strip on ultimate strength is shown in section 3.6.

4.5.1 Effect of Combination of Two on Ultimate Strength

Finally, different number of horizontal strips are provided in the encased stone column of encasement length 4D with a spacing of half of diameter of stone column. The load settlement curve for various encased stone column with different number of horizontal strips varying from 1 to 6 has been analysed. Fig. 4.18 shows curves of load settlement for c_u=7 kPa with various number of horizontal circular strips. There is no significant increase in the ultimate strength of stone column with increase in number of horizontal circular strips. Fig. 4.19 shows the load settlement curve for c_u=14kPa with various number of horizontal circular strips. It is clearly visible that there is no significant increase in ultimate strength after 2 horizontal strips. However, in Fig. 4.20, which shows the load settlement curve for c_u=30kPa with various number of horizontal circular strips, the ultimate strength increases with increase in number of horizontal strips.

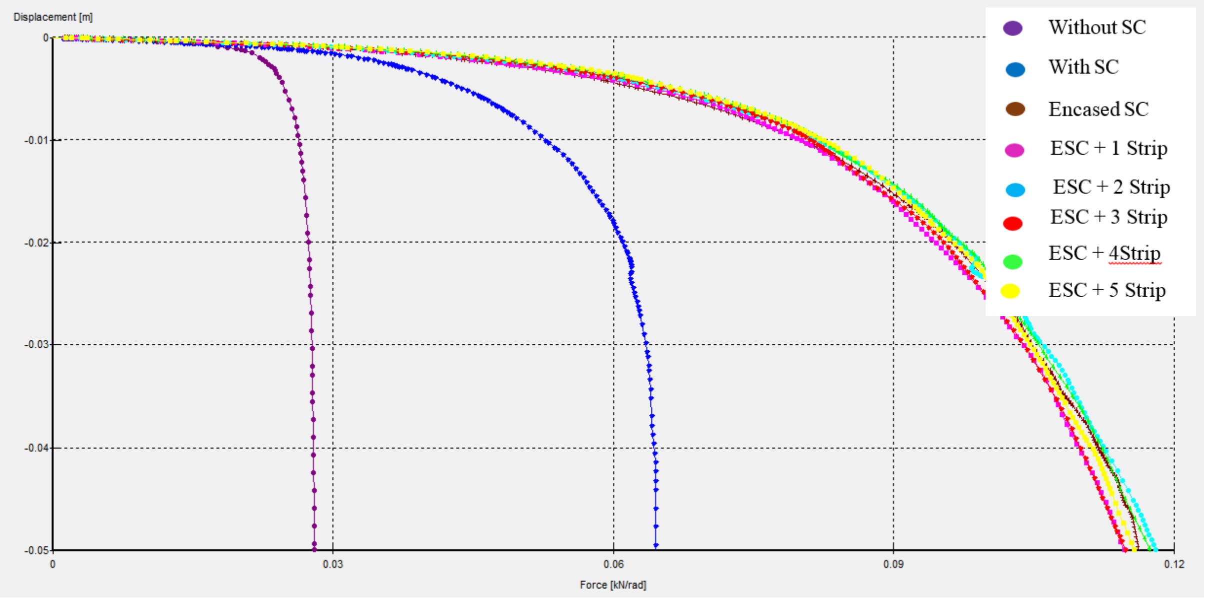

Fig. 4.18 Load settlement curve for different number of horizontal strips in encased stone column for c_u=7 kPa

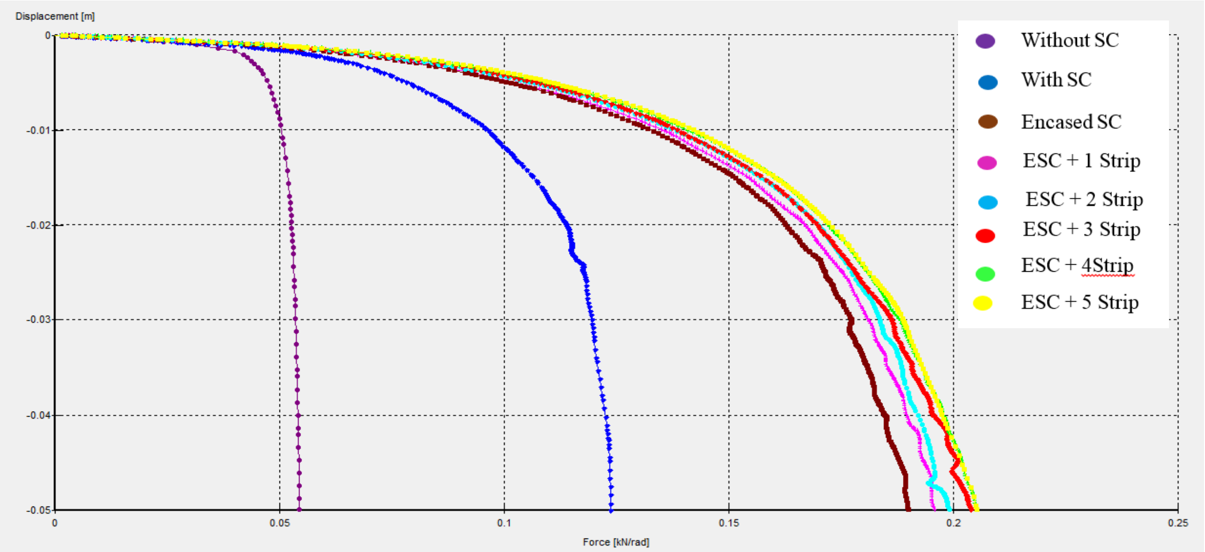

Fig. 4.19 Load settlement curve for different number of horizontal strips in encased stone column for c_u=14 kPa

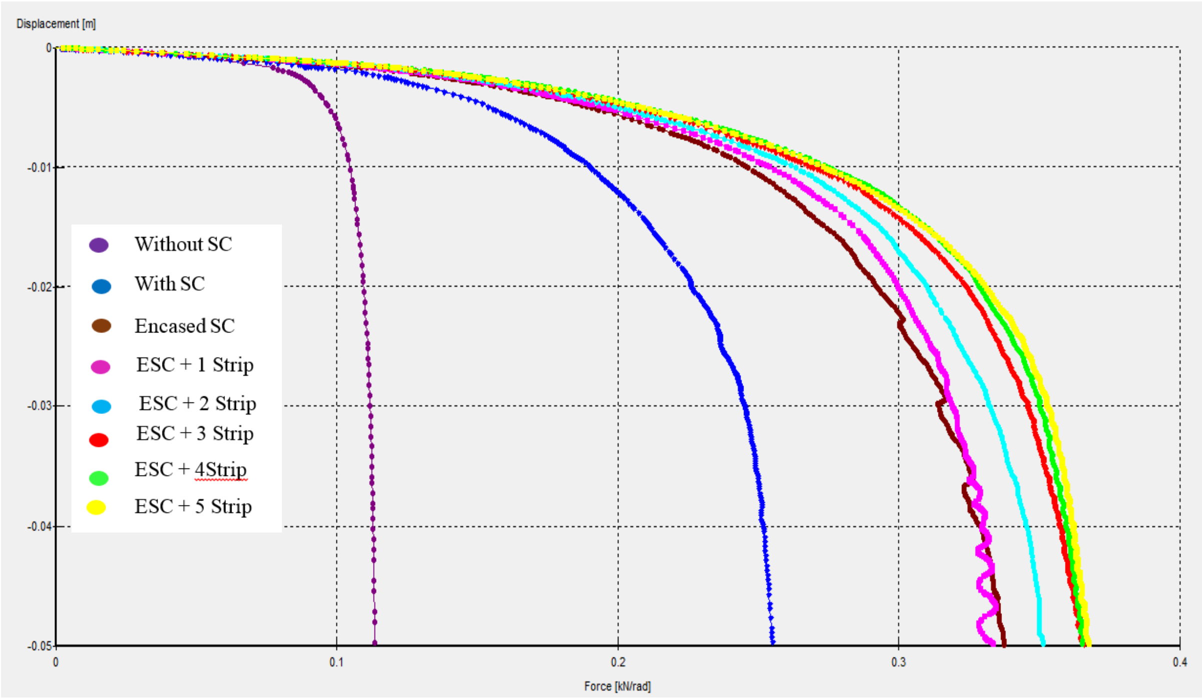

Fig. 4.20 Load settlement curve for different number of horizontal strips in encased stone column for c_u=30 kPa

CHAPTER 5

CONCLUSION

5.1 CONCLUSIONS

The present work describes the finite element analysis carried out to study the effect shear strength of soil, diameter ratio, external reinforcement by raping the stone column and internal reinforcement by providing horizontal circular strips on the bulging behavior of stone column and load carrying capacity. Based on the results obtained from this study the following conclusions are made:

1. For low strength of soil (soft soil), as geogrid encasement length increases, the ultimate strength of stone column increases. Although, the rate of increament of ultimate strength decreases with increased encasement length. But for high strength of soil (stiff soil), partial encasement in upper portion of stone column is more effective.
2. For soft soil, as number of horizontal circular strips increases the ultimate strength increases and found reinforcement over the full column length gives higher ultimate strength but, for stiff soil, reinforcement in upper region is effective.
3. Combination of external reinforcement (circumferential encasement) and internal reinforcement (horizontal circular strips) is more effective in stiff soil rather than soft soil.

5.2 SCOPE OF FUTURE WORK

- Modeling of group of stone column with encasement and without encasement.
- Position of horizontal circular reinforcement can be changed in the encased stone column.

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